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# Parametric amplification and phase preserving amplitude regeneration of a 640 Gbit/s RZ-DPSK signal

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## Abstract:

We report the first experimental demonstration of parametric amplification and all-optical phase-preserving amplitude regeneration for a 640 Gbit/s return-to-zero (RZ) differential phase-shift keying (DPSK) optical time division multiplexed (OTDM) signal. In the designed gain-flattened single-pump fiber optical parametric amplifier (FOPA), 620 fs short optical pulses are successfully amplified with 15 dB gain with error-free performance and less than 1 dB power penalty. Phase-preserving amplitude regeneration based on gain saturation in the FOPA is carried out for optical signals with degraded optical signal-to-noise ratio. An improvement of 2.2 dB in receiver sensitivity at a bit-error-ratio of  $10^{-9}$  has been successfully achieved after regeneration, together with 13.3 dB net gain.

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## 1. Introduction

Fiber optical parametric amplifiers (FOPAs) have proved themselves as multi-functional devices not only for amplification of optical signals with high gain, wide bandwidth, flexible operation spectral band and low noise, but also as all-optical signal processing subsystems for frequency conversion, demultiplexing and regeneration [1–3]. In particular, the quasi instantaneous gain response of FOPAs makes them attractive for all-optical regeneration of ultra-fast signals, for instance in high-speed optical time division multiplexed (OTDM) systems.

All-optical regeneration is one of the desired functionalities to extend the transmission distance in high-capacity optical networks without resorting to optical-electrical-optical conversions, which are increasingly challenging to implement at ultra-high bit rates. During propagation through long-haul transmission links, optical signals are degraded due to various impairments, such as amplified spontaneous emission (ASE) noise added by in-line amplifiers, nonlinear effects such as self- and cross-phase modulation, and chromatic dispersion imposed by the transmission medium and other dispersive elements. These impairments introduce waveform distortion, amplitude jitter, timing jitter and extinction ratio (ER) degradation to the transmitted signal. A regenerator is therefore required to restore the quality of the signal. Regeneration

with functionalities including reamplification and reshaping, referred to as 2R regeneration, contributes to the suppression of amplitude jitter and ER enhancement plus amplification.

So far, the highest total data capacity to be amplified in a single-pump FOPA has consisted of 26 wavelength-division-multiplexed (WDM) return-to-zero differential-phase-shift-keying (RZ-DPSK) modulated signals at 43.7 Gbit/s [4] resulting in a total data rate of 1.1 Tbit/s. Crosstalk mainly limits the amplification performance of WDM signals in parametric amplifiers due to four-wave mixing (FWM) between the channels [5, 6]. In contrast, OTDM signals are not subjected to crosstalk as all the channels are time interleaved and the FOPA response is instantaneous.

FOPAs operating in the saturation regime have been used for optical level equalization and amplitude noise suppression [7, 8], accompanied with signal gain. The scheme preserves the wavelength and phase of the signal. Amplitude noise suppression for phase modulated signals, i.e. using the DPSK or differential quadrature phase-shift (DQPSK) formats where all the symbols have an identical intensity pattern, is also achievable in gain saturated FOPAs [9–11], ideally without affecting the phase information of the signal. Amplitude-only regeneration of phase modulated signals is effective as it prevents the conversion of amplitude fluctuations to phase fluctuations through the fiber non-linearities, an effect known as nonlinear phase noise [12], and thus is able to improve the transmission performance of the signal.

Phase-preserving amplitude regeneration (PPAR) for phase-modulated signals has been demonstrated using different schemes. PPAR based on optical injection locking for 10 Gbit/s binary phase-shift keyed (BPSK) signals [13], or on a semiconductor optical amplifier for 40 Gbit/s DPSK signals [14], have been recently reported. So far, the highest bit rate at which single-channel all-optical regeneration has been achieved is 640 Gbit/s, using a periodically-poled lithium niobate (PPLN) waveguide [15]. Regeneration of a total capacity of 640 Gbit/s has also been demonstrated based on saturated FWM in a highly-nonlinear fiber (HNLF) [16], albeit using wavelength and polarization multiplexing. In both cases, regeneration was realized for on-off keying data signals and accompanied with no amplification. Even though FOPAs can simultaneously amplify and regenerate degraded signals thanks to the ultra-fast process of their gain saturation, which makes them highly suitable for high bit-rate applications [1], the regeneration of high-speed short pulses based on saturated FOPAs can be challenging, mainly due to the limited uniform gain bandwidth available in single-pump FOPAs and the generation of undesirable higher-order FWM products falling in the bandwidth of the data signal in dual-pump FOPAs.

This paper extends our previous work in [17] and explores for the first time the use of single-pump FOPAs for the amplification and regeneration of a single wavelength channel 640 Gbit/s RZ-DPSK OTDM signal. The broad spectrum associated with such a signal requires optical signal processors with compatible operation bandwidths. For this purpose, a gain-flattened single-pump FOPA is first designed for the amplification of a 640 Gbit/s signal consisting of pulses as short as 620 fs. The amplification performance and gain shaping is investigated for different gain levels. Then, PPAR is demonstrated in the designed FOPA with a 10 nm saturated gain bandwidth with gain flatness better than 1 dB. Regeneration is studied for degraded signals with different levels of input optical signal-to-noise ratio (OSNR). Error free performance with less than 1 dB power penalty is achieved in the amplification of the 640 Gbit/s RZ-DPSK signal. Improvement of 2.2 dB of the receiver sensitivity at a bit-error-ratio (BER) of  $10^{-9}$  along with 13.3 dB net gain are successfully demonstrated.

This paper is organized as follows. Section 2 describes the experimental setup for amplification and regeneration of a 640 Gbit/s OTDM signal. The static gain spectrum of the designed FOPA is discussed in Section 3. Amplification performance and all-optical regeneration of the 640 Gbit/s signal are presented in Sections 4 and 5, respectively. Finally, conclusions are drawn

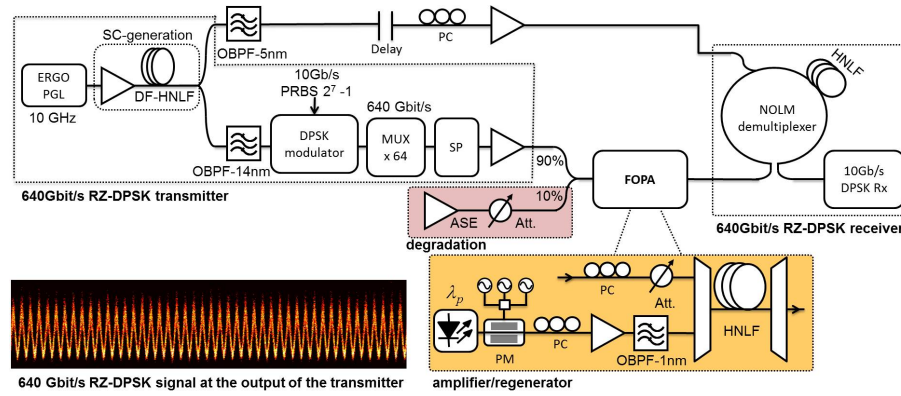


Fig. 1. Experimental setup for amplification of a 640 Gbit/s RZ-DPSK signal using a FOPA.

in Section 6.

## 2. Experimental setup

The experimental setup for amplification and regeneration of a 640 Gbit/s RZ-DPSK signal is illustrated in Fig. 1. It consists of a 640 Gbit/s transmitter, a FOPA, a non-linear optical loop mirror (NOLM) demultiplexer and a 10 Gbit/s receiver. At the transmitter, 10 GHz short pulses are generated from an erbium glass oscillating pulse-generating laser (ERGO-PGL) at 1542 nm with  $\sim 1.5$  ps full width at half maximum (FWHM) pulse width. The short pulses are amplified and launched into a 400 m dispersion-flattened highly non-linear fiber (DF-HNLF) to broaden their spectrum through self-phase modulation. The broadened spectrum is filtered at 1553 nm and 1542 nm with 14 nm and 5 nm optical bandpass filters (OBPFs) to generate two 10 GHz pulse trains to be used as the data signal and the NOLM demultiplexer control pulses, respectively. The data signal is encoded at 10 Gbit/s in the DPSK modulation format using a  $2^7-1$  pseudo-random binary sequence (PRBS) and then time multiplexed up to 640 Gbit/s using a PRBS-preserving passive fiber-delay multiplexer. The dispersion accumulated in the transmitter is compensated and the signal is spectrally shaped using an optical signal processor (SP), amplified and input to the FOPA for amplification characterization. In case of regeneration characterization, the signal is intentionally degraded by combining it with ASE noise originating from an erbium-doped fiber amplifier (EDFA) via a 90/10% coupler (shown as a pink box in Fig. 1). The OSNR of the signal at the FOPA input is adjusted by a variable attenuator placed after the ASE source in the degradation setup.

At the FOPA, the pump is a continuous wave (CW), which is phase modulated by three frequency tones (106 MHz, 288 MHz and 1 GHz) in order to increase the stimulated Brillouin scattering threshold. Other techniques for increasing the stimulated Brillouin scattering threshold could be used instead of pump frequency dithering. However, techniques such as fiber straining may change the dispersion profile of the fiber. Since precise dispersion characteristics of the HNLF are needed to design a wideband amplifier for amplification of the high bit rate OTDM signal, such a method may cause ZDW fluctuations along the fiber, or possibly increase the polarization mode dispersion of the HNLF.

The pump is then amplified and filtered with a 1 nm OBPF, to remove out-of-band ASE noise, and coupled by a WDM coupler with the signal into the HNLF used as gain medium. The OSNR of the pump is 54 dB and its input power to the HNLF is 27 dBm. The HNLF is 500 m long, with

zero-dispersion wavelength (ZDW) at 1569 nm, dispersion slope of  $0.016 \text{ ps} \cdot \text{nm}^{-2} \cdot \text{km}^{-1}$ , non-linear coefficient of  $11.4 \text{ W}^{-1} \cdot \text{km}^{-1}$  and loss of  $0.7 \text{ dB} \cdot \text{km}^{-1}$ . At the output of the FOPA, the amplified signal is filtered by cascading two WDM couplers to suppress the pump wave without affecting the signal spectrum. The amplified 640 Gbit/s OTDM signal is demultiplexed in the NOLM, operating based on cross-phase modulation induced in a 50 m HNLF by a 10 GHz control pulse train obtained by filtering the initial broadened pulse source spectrum, resulting in 10 Gbit/s RZ-DPSK signals. Finally, the demultiplexed signals are demodulated and detected using a 1-bit delay interferometer and a balanced photodetector.

### 3. Static gain spectrum

In order to amplify and regenerate high-speed OTDM signals consisting of very short pulses using FOPAs, an amplifier with flat gain and free from any overlap with higher-order FWM products (HFPs) in saturation is required. Concerning the gain flatness in single-pump FOPAs, the gain bandwidth can be tuned for a given HNLF by tuning the wavelength and power of the pump, which determine the balance between the linear ( $\Delta\beta$ ) and non-linear ( $2\gamma P_p$ ) phase-mismatch terms  $\Delta\beta + 2\gamma P_p = 0$ . Pumping the amplifier close to the ZDW can broaden the gain spectrum at the expense of losing gain due to longitudinal fluctuations of the ZDW [18].

At first, static gain spectra are measured using a swept CW probe signal for different signal input powers to the HNLF ( $P_s$ ), as shown in Fig. 2(a). The pump wavelength is set 2.5 nm above the ZDW at 1571.5 nm in order to provide a fairly flat gain spectrum around the signal wavelength centered at 1553 nm. The 1 dB gain bandwidths for  $P_s = -15 \text{ dBm}$ ,  $+7 \text{ dBm}$  and  $+9 \text{ dBm}$  are 8 nm, 10 nm and 15 nm, respectively. The flatter gain spectrum obtained for higher input signal powers is due to the fact that saturation occurs faster for the parts of the signal spectrum with the highest gain.

The other factor that needs to be ensured in processing short pulses in FOPAs is the proper frequency separation between the pump and signal. The signal spectral bandwidth needs to be

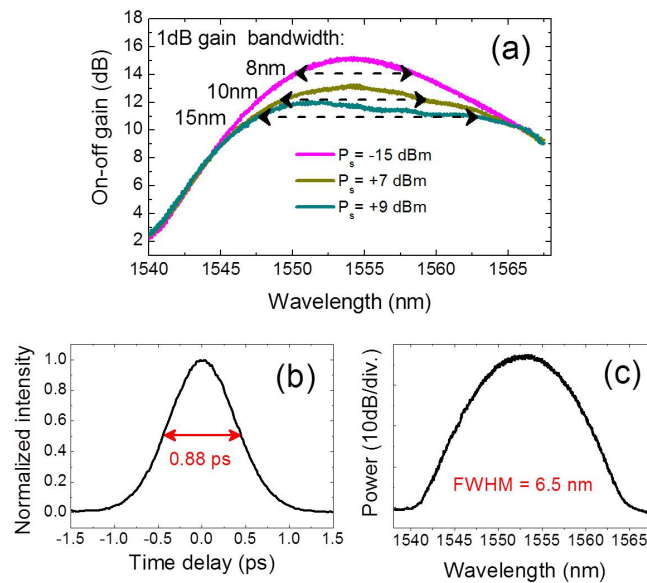


Fig. 2. (a) Static gain spectra for different signal input powers. (b) Autocorrelation trace and (c) spectrum of the 640 Gbit/s OTDM signal at the input of the FOPA.



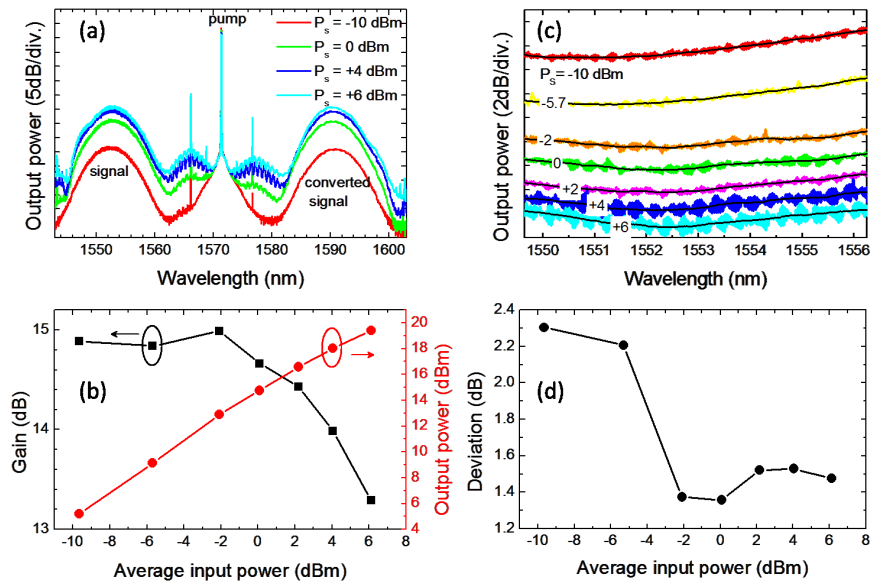


Fig. 3. (a) Output spectra of the FOPA for different signal input power values. (b) Signal output power and signal gain as a function of signal input power to the FOPA. (c) Differences between the FOPA input and output signal power spectra within the FWHM range of the input signal spectrum. (d) Peak-to-peak values of the power spectrum differences.

separated enough from the pump so that the new generated waves, resulting from interaction between the pump and a part of the signal spectrum close to the pump, does not overlap with the other side of the signal spectrum. The autocorrelation trace and spectrum of the 640 Gbit/s signal input to the FOPA are shown in Figs. 2(b) and 2(c). The input signal has a Gaussian pulse shape with 620 fs temporal (880 fs autocorrelation) and 6.5 nm spectral FWHM. The signal is centered at 1553 nm, which corresponds to a 18.5 nm wavelength separation from the pump. This wavelength separation is equal to about three times the signal spectral FWHM. This separation ensures no overlap of the new generated waves in saturation within twice the signal spectral FWHM.

It is worth mentioning that in the amplification of high bit rate OTDM signals using FOPAs, the pulse width of the base rate signal is an important factor regardless of its repetition rate, because the bandwidth of the amplifier needs to be compatible with the signal bandwidth, which is independent of its repetition rate.

#### 4. Amplification of a 640 Gbit/s RZ-DPSK signal

Once an amplifier with sufficient flat gain bandwidth has been designed, amplification of a 640 Gbit/s signal consisting of pulses as short as 620 fs is investigated in this section. The amplification performance for the 640 Gbit/s RZ-DPSK signal is studied at different gain levels in order to investigate the effect of gain shaping in the saturated regime.

##### 4.1. Effect of gain shaping

The output spectra of the FOPA for different signal input power levels are shown in Fig. 3(a). The maximum gain is achieved for the signal with  $-10$  dBm average input power and is about

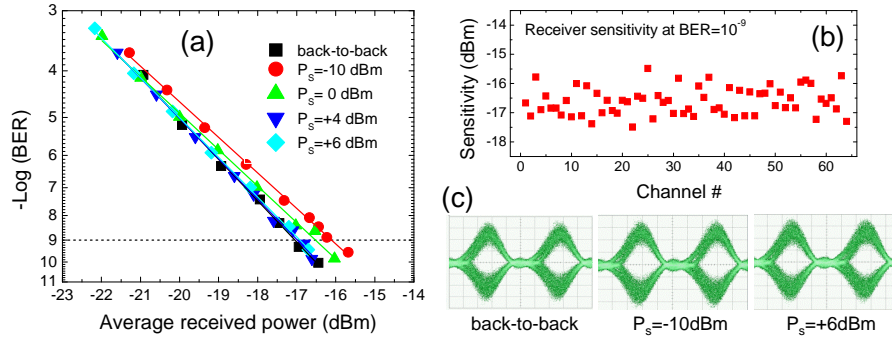


Fig. 4. (a) BER measurements for a 10 Gbit/s DPSK channel demultiplexed from the 640 Gbit/s signal. (b) Receiver sensitivity at a BER of  $10^{-9}$  in back-to-back configuration. (c) Eye-diagrams of demultiplexed and demodulated signals for back-to-back and after amplification with  $-10$  dBm and  $+6$  dBm input power.

15 dB (net gain measured between the FOPA input and output, as defined in Fig. 1). The average output power and signal gain, measured in a 14 nm spectral window, are shown as a function of the average signal input power in the inset of Fig. 3(b). The signal gain is decreased by 1.7 dB by increasing the signal input power up to  $+6$  dBm.

To investigate the effect of the gain shaping on the amplified signal, the difference between the input spectrum to the FOPA and the amplified spectrum was examined within the FWHM range of the input signal spectrum (i.e. 6.5 nm) for different signal input powers, as shown in Fig. 3(c). The extracted peak-to-peak deviation of this power difference (i.e. power difference between the input and the amplified spectrum within the FWHM range of the input signal) is represented in Fig. 3(d). As the signal input power increases and the gain spectrum becomes flatter, the peak-to-peak deviation consequently decreases, resulting in reduced spectral shaping. The notable point here is the clear spectral shaping of the amplified signal for input signal powers above  $-2$  dBm, while the signal gain (calculated based on the average input and output powers) does not show significant saturation at this power. At this power, the effect of the localized saturation of the FOPA gain does not result in a gain drop for the signal average power but does significantly alter the shape of the gain spectrum. It appears that, at a signal power of about  $-2$  dBm, it is possible to achieve both high average gain and a flat gain spectrum for this FOPA configuration.

#### 4.2. Bit-error-ratio performance

Figure 4(a) shows the results of bit-error-ratio (BER) measurements as a function of the average received power at the input of the demultiplexer for the 10 Gbit/s demultiplexed signal. The back-to-back curve was measured when the pump was off and the input signal power to the HNLF was set to  $+5$  dBm. The receiver sensitivities at a BER of  $10^{-9}$  of all the 64 demultiplexed channels are shown in Fig. 4(b). Sensitivities for all the channels are spread within  $\sim 2$  dB. The rest of the measurements are performed for channel number 2 with  $-17.1$  dBm back-to-back sensitivity. Amplification with 15 dB net gain and less than 1 dB power penalty compared to back-to-back is successfully achieved for  $P_s = -10$  dBm. The performance of the system is even closer to the back-to-back case when the signal input power is increased, reaching about 0.1 dB penalty for  $P_s = +6$  dBm. In fact, the signal is more affected by the intensity noise transfer from the pump in the unsaturated gain regime. Increase of the signal input power to the FOPA reduces the pump-to-signal noise transfer and flattens the gain spectrum,



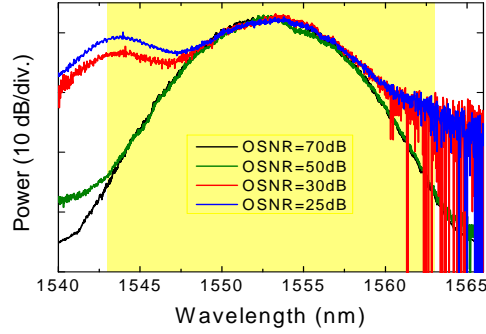


Fig. 5. Spectra of the 640 Gbit/s OTDM signals input to the FOPA for different OSNRs. Yellow region: the bandwidth in which the OSNR is evaluated.

as shown above, resulting in better signal performance at the expense of 1.7 dB of signal gain. The eye diagrams of the 10 Gbit/s demultiplexed and demodulated signals at a BER of  $10^{-9}$  are also shown in Fig. 4(c) for back-to-back and amplified signals with 15 dB and 13.3 dB gain, corresponding to  $P_s = -10$  dBm and +6 dBm, respectively.

## 5. Regeneration of a 640 Gbit/s RZ-DPSK signal

In a transmission link, amplitude noise can be converted to nonlinear phase noise through the Kerr non-linearity of the transmission fibers (self-phase and cross-phase modulations), which adversely affects the phase information of the signal [12]. Therefore, PPAR of phase encoded signals can mitigate the accumulation of nonlinear phase noise along the link. The effectiveness of phase-preserving amplitude regenerators for DPSK signals is proved by placing the regenerator either before some transmission spans [13, 19, 20] or before the receiver [9, 10, 21–23]. In the first case, amplitude regeneration prevents the conversion of amplitude noise to phase noise during transmission. On the other hand, when PPAR is located at the receiver, the effect of the amplitude regeneration is actually verified through the reduction of the amplitude noise on the output current of the balanced receiver [22]. In this section, PPAR based on the latter scheme is demonstrated for the first time for a 640 Gbit/s RZ-DPSK signal using a single-pump FOPA.

### 5.1. Degraded input signal

The regeneration is evaluated for signals with different OSNR levels input to the FOPA. The clean and degraded input signal spectra to the FOPA, which are measured by an optical spectrum analyzer with 0.1 nm resolution bandwidth, are shown in Fig. 5. The OSNR was calculated by integration of the signal and noise powers ( $P_{signal}$  and  $P_{noise}$ , respectively) over a 20 nm bandwidth ( $\Delta\nu_{power}$ ) represented in yellow in Fig. 5, and normalization of the noise power to a 0.1 nm reference bandwidth ( $\Delta\nu_{ref.}$ ) according to

$$OSNR = \frac{P_{signal}}{P_{noise} \times \frac{\Delta\nu_{ref.}}{\Delta\nu_{power}}}. \quad (1)$$

The clean signal corresponds to the case with no loaded noise and has an OSNR of 70 dB. Three levels of degradation are set at the input of the regenerator, corresponding to reduced OSNR values of 50 dB, 30 dB and 25 dB. For the highly degraded signals with 30 dB and 25 dB of OSNRs, the output of a high-power EDFA is used as ASE source, while for the lower noise levels a preamplifier EDFA is used, resulting in the differences seen on the short-wavelength

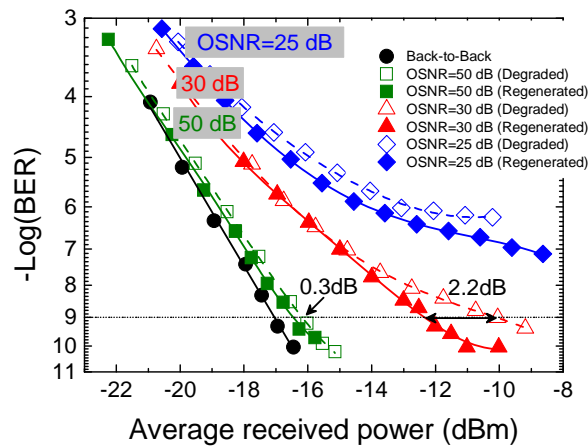


Fig. 6. BER measurements for a 10 Gbit/s DPSK channel demultiplexed from the degraded 640 Gbit/s signal for different levels of input OSNR, as well as after regeneration.

side of the signal spectra. The measurement of the OSNR is based on the noise level of the EDFA located before the FOPA (acting as ASE source). As it will be shown later, the BER performance of the system is affected by the presence of the noise loading ASE source, which confirms that the signal in-band noise level is dominated by this source.

## 5.2. Bit-error-ratio performance

Figure 6 shows the results of BER measurements for the 10 Gbit/s demultiplexed signal as a function of the average received power (measured at the input of the demultiplexer). The back-to-back curve was measured for the noise-free signal when the pump was off and the input signal power to the HNLF was set to +5 dBm. The rest of the measurements are performed for channel number 2 with -17.1 dBm back-to-back sensitivity. When the signal is not regenerated, the input signal average power is set to -10 dBm, while it is equal to +6 dBm in order to reach saturation and demonstrate regeneration. The slightly degraded signal, with OSNR = 50 dB, shows almost no sensitivity difference (< 0.3 dB) before and after regeneration, indicating that no regeneration is needed for this input OSNR level. When the input OSNR is reduced to 30 dB, the regeneration improves the received sensitivity by 2.2 dB, showing the effectiveness of the scheme at improving the quality of the degraded signal. For more degraded signals, i.e. OSNR = 25 dB, the distortion is too high to be regenerated and no error-free performance was possible.

The spectra measured at the output of the FOPA HNLF for the amplified clean signal, the degraded signal with OSNR = 30 dB and the corresponding regenerated signal are depicted in Fig. 7. Amplification of 13.3 dB has been measured for the regenerated signal. The two tones visible around the pump at 1565 nm and 1576 nm are due to cross-phase modulation with the 640 Gbit/s signal and are thus separated from the pump by 640 GHz. The other tones at the edges of the spectrum are due to excitation of higher-order FWM products in saturation.

## 6. Conclusions

In this paper, amplification and PPAR of a 640 Gbit/s RZ-DPSK OTDM signal in a single-pump FOPA has been demonstrated for the first time to our knowledge. The performance of the am-

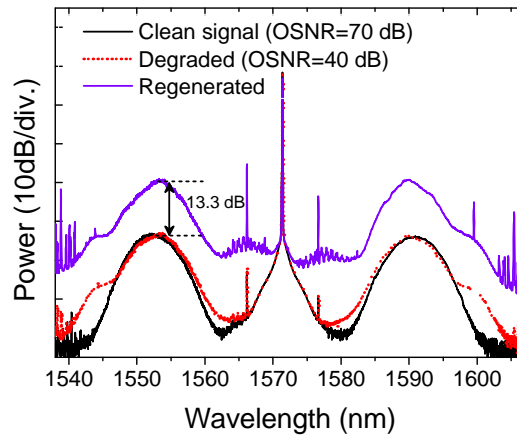


Fig. 7. Output spectra of the FOPA for the amplified clean signal (OSNR=70 dB), degraded signal (OSNR=40 dB) and corresponding regenerated signal with 13.3 dB amplification.

plifier for different gain levels has been investigated. The effect of parametric gain saturation for the 620 fs interleaved pulses has been investigated by characterizing the effect of gain shaping. For the 6.5 nm FWHM spectrally broad signal, we found that the gain saturation manifests its effect through the shaping of the signal spectrum. On the other hand, the consideration of the evolution of the average output power integrated over the signal bandwidth does not allow to fully capture the effect of saturation, as would be the case for a monochromatic or spectrally narrow signals. Parametric amplification of the 640 Gbit/s RZ-DPSK signals was evaluated by BER characterization. Error-free performance with 15 dB net gain has been achieved with less than 1 dB power penalty, which was further reduced to almost no penalty when the gain was saturated by 1.7 dB. PPAR has also been demonstrated for the 640 Gbit/s RZ-DPSK signal based on a gain optimized single-pump FOPA. For the degraded signal with 40 dB reduced OSNR, the receiver sensitivity has been improved by 2.2 dB by the regenerator, simultaneously providing 13.3 dB of gain.

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